The Long and the Short of Gamma-Ray Bursts

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ABSTRACT

We report evidence from the 3B Catalogue that long ($T_{90} > 10$ s) and short ($T_{90} < 10$ s) gamma-ray bursts represent distinct source populations. Their spatial distributions are significantly different, with long bursts having $\langle V/V_{max}\rangle = 0.282 \pm 0.014$ but short bursts having $\langle V/V_{max}\rangle = 0.385 \pm 0.019$, differing by 0.103 ± 0.024, significant at the $4.3\,\sigma$ level. Long and short bursts also differ qualitatively in their spectral behavior, with short bursts harder in the BATSE (50–300 KeV) band, but long bursts more likely to be detected at photon energies > 1 MeV. This implies different spatial origin and physical processes for long and short bursts. Long bursts may be explained by accretion-induced collapse. Short bursts require another mechanism, for which we suggest neutron star collisions. These are capable of producing neutrino bursts as short as a few ms, consistent with the shortest observed time scales in GRB. We briefly investigate the parameters of clusters in which neutron star collisions may occur, and discuss the nuclear evolution of expelled and accelerated matter.

Subject headings: gamma-ray bursts; neutron stars

1. Introduction

Kouveliotou *et al.* 1993 found that the durations of "classical" gamma-ray bursts[1] (GRB) are bimodally distributed and are anti-correlated with their spectral hardness as measured by BATSE in the 50–300 KeV band. These authors found no statistically significant differences between the spatial distributions of long and short GRB.

Little attention has been paid to the cause of the division of GRB into two classes, long and short. The simplest interpretation is that all GRB are of similar origin, but have different values of one or more bimodally distributed parameters (for example, the interstellar density [Katz 1994a] or the shock parameters [Sari & Piran 1995]). Most models of GRB have several poorly determined parameters. The observed anti-correlation of duration with spectral hardness is naturally obtained in the neutrino-fireball-debris-shock (NFDS) process (Rees & Mészáros 1992, Mészáros & Rees 1993, Katz 1994a) in which a higher Lorentz factor Γ leads to a shorter GRB and to a higher characteristic synchrotron frequency ν_{Synch}.

The most popular NFDS models have been based on coalescing neutron stars (Eichler *et al.* 1989). However, in gravitational radiation-driven coalescence of a binary star the radial component of relative velocity of the stars is subsonic with respect to their interior sound speed. Unless the viscosity is spectacularly large ($\sim 10^{29}$ gm cm^{-1} s^{-1}), the flow is nearly adiabatic, with little heating or neutrino emission. The only strong shock expected would be where a mass-transfer stream strikes an accreting star or disc, a process which does not occur for stars of similar mass and radius, as in a neutron star binary. Three-dimensional hydrodynamic calculations (Janka & Ruffert 1996, Mathews *et al.* 1996) confirm this conclusion; there is insufficient heating or neutrino emission to create an energetic fireball.

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[1]This paper does not discuss soft gamma repeaters.

Accretion-induced collapse (AIC) of a bare degenerate dwarf has been calculated (Dar *et al.* 1992) to produce sufficient neutrino flux to power a fireball. AIC produces a ~ 10 s neutrino burst, as observed from SN1987A (the presence of a stellar envelope turns the neutrino energy into a supernova, while its absence permits a relativistic fireball). The duration of neutrino emission is a lower bound on the duration of the resulting GRB because the subsequent shock interaction, particle acceleration and radiation can stretch the observed GRB (as will the cosmological redshift), but cannot so readily shorten it. We note that AIC is much more frequent than GRB, which require that the collapse be surrounded by the right density of matter to produce a relativistic baryonic shell.

AIC can therefore explain only long GRB with $T_{90} > 10$ s; shorter GRB require a different process. Both long and short GRB must occur at "cosmological" distances (great enough that the geometry of space is non-Euclidean or cosmological evolution is significant) because each class is isotropically distributed on the sky and has $\langle V/V_{max} \rangle < 0.5$ (Kouveliotou *et al.* 1993). Both probably produce soft (< 1 MeV) gamma-rays by the NFDS process, explaining their qualitatively similar soft gamma-ray spectra and complex pulse forms, but the origins of the energy must be different.

The purpose of this paper is to investigate the hypothesis that long and short GRB have different physical origins. In §2 we compare their spectra at soft and harder gamma-ray energies, and find a qualitative difference. In §3 we compare their distributions in space, and find a quantitative difference, although both classes are at "cosmological" distances. These two independent conclusions each confirm our hypothesis that short and long GRB are the result of different events. AIC is discussed as the origin of long GRB in §4. Short GRB require a new process, for which we suggest colliding neutron stars in §5. The nuclear composition of expelled and accelerated matter, and its implications for GRB, are briefly estimated in §6. §7 contains a general discussion.

2. Spectral Behavior

If long and short GRB are produced by two distinct kinds of events, members of these two classes may have qualitatively different spectral properties. This hypothesis can be tested with data in the 3B catalogue (Meegan *et al.* 1996). We find that there are indeed qualitative differences between the spectral properties of long and short GRB.

The BATSE hardness ratio is a measure of the spectral slope in the range 50–300 KeV. Some of the bursts in the 3B catalogue were also detected by COMPTEL, EGRET and OSSE, indicating the presence of energetic photons above the BATSE band. The data are summarized in Table 1. The choice of a BATSE hardness ratio criterion of 10 in the first line of the Table selects the very hardest BATSE spectra, but is necessarily arbitrary. This was a natural choice when we first scanned the data by eye, and we have retained it.

It is evident that long and short GRB differ qualitatively. Considering only the BATSE and COMPTEL detections, the probability of this distribution (or of a greater difference between short and long GRB) being obtained from a single population of events is $< 10^{-8}$. The EGRET detections strengthen this conclusion, while the two OSSE detections contribute little information. We cannot, however, exclude the possibility of a systematic bias in detection thresholds of COMPTEL (in comparison to BATSE) in favor of detection of long GRB.

Photons with energies > 1 MeV are detected almost exclusively from long ($T_{90} > 10$ s) GRB. This is opposite to the behavior expected from an extrapolation of the hardness measured at lower photon energies by BATSE. Long and short GRB show qualitatively different spectral behavior, which cannot be explained by variation of a single parameter, such as ν_{Synch}. We conclude that different physical processes must be involved, rather than different parameter ranges of a single process.

3. Spatial Distributions

If long and short GRB have distinct physical origins they may have distinct spatial distributions, although this is not specifically predicted. Table 2 presents the results of an analysis of the C/C_{min} data in the 3B Catalogue (Meegan *et al.* 1996). The Whole Catalogue analysis shows that $\langle V/V_{max}\rangle$ for long and short GRB differ by $4.3\,\sigma$, which is very unlikely to be a statistical fluctuation. Long and short GRB are thus found to have different spatial distributions, and therefore must originate in different classes of events.

We analyzed the positional data in the 3B Catalogue separately for long and short GRB, and found no statistically significant dipole or quadrupole deviations from isotropy for either class (confirming the result of Kouveliotou *et al.* 1993). We conclude that both classes are at "cosmological" distances, but that long GRB are more deficient in faint bursts, and are therefore closer, on average. This presumably reflects differences in the cosmological evolution of the two source populations.

C. Kouveliotou (private communication) suggested that we subdivide the data on the basis of integration times, as shown in Table 2. This shows that small $\langle V/V_{max}\rangle$ is chiefly a property of the subpopulation of smoothly rising GRB (most of which are also long), which are defined by the criterion that they do not trigger the detector when short integration times (64 ms) are used. We can predict that if these "smooth risers" could be separated from other long GRB they would have even smaller $\langle V/V_{max}\rangle$, and would be a pure AIC population, uncontaminated by GRB which have an intrinsically short time scale (and hence rapid rise) but whose T_{90} is long because they radiate slowly or have multiple widely separated subpulses. Individual identification of "smooth risers" would require the complete time-histories of each GRB, and would be difficult because of the limited signal-to-noise ratio of most GRB.

4. Long GRB

Any model of long GRB must explain their > 1 MeV emission by a process distinct from that which produces their lower energy emission. This process must occur only in long GRB, implying that their physical environment is fundamentally different from that of short GRB. Such a model was developed (Katz 1994b) for the extraordinarily intense burst 3B940217, which was very long ($T_{90} = 150$ s) as measured by BATSE, and which also produced photons of energies as high as 18 GeV an hour after the initial burst (Hurley *et al.* 1994), but which had the unremarkable BATSE hardness ratio of 3.83. In this model the energetic gamma-rays are attributed to π^0 decay or to Compton scattering by energetic electrons and positrons (themselves produced by $\pi^\pm$ decay) resulting from relativistic nuclei (fireball debris) colliding with baryons in a dense cloud of circumfireball matter. We now suggest that such a model is applicable to many or all long GRB (but no short GRB), though the density and geometry of the cloud will necessarily vary from event to event, as will therefore the efficiency of production of energetic gamma-rays.

The cloud was attributed to excretion by the progenitor of one of the neutron stars in a coalescing neutron star model. That specific scenario must be replaced by one of AIC: when matter flows into an accretion disc surrounding the degenerate dwarf a fraction f of it is excreted from the disc and the binary. This is inevitable; matter accreting onto the dwarf must give up nearly all its angular momentum, which flows outward by viscous stress in the accretion disc. Conservation of angular momentum gives

$$f = 1 - (r_{RCR}/r_{LSO})^{1/2}, \tag{1}$$

where r_{RCR} is the Roche circularization radius (Katz 1973) and r_{LSO} is the radius of the last stable disc orbit (Bahcall *et al.* 1974), from which mass peels off the disc and is lost; $f \approx 0.5$, almost independent of the binary mass ratio.

The circumfireball cloud must be rather small ($< 10^{15}$ cm) in order that it be dense enough for collisional interaction with the relativistic debris. For energetic collisional gamma-rays detected simultaneously with a 30 s GRB the time of flight suggests a size $\sim 10^{12}$ cm, but this may be an underestimate (by a factor up to Γ^2) if the relativistic particles are moving radially outward at the time of collision; as a result, the time of flight may not give a useful bound on the cloud dimensions. However, the requirement of collisional interaction gives a secure lower bound to the density and therefore, for reasonable cloud masses, an upper bound to the cloud's dimensions, independent of any assumptions about relativistic kinematics.

A degenerate dwarf cannot accrete hydrogen-rich matter at a rate faster than $3 \times 10^{-7} M_\odot$ y^{-1} because the Eddington limit bounds its thermonuclear luminosity. As a result, AIC is likely to be preceded by a period of accretion of order the Eddington time (Katz 1987)

$$t_E = \frac{\epsilon c \kappa}{4\pi G} \approx 3 \times 10^6 \text{ y}, \tag{2}$$

where ϵc^2 is the thermonuclear energy release per gram and κ is the opacity. It is not known how close to the Chandrasekhar limit is the degenerate dwarf when it begins accretion, but known degenerate dwarfs are at least a few tenths of $M_\odot$ below that limit, implying accretion over at least $\sim 10^6$ y.

Even the largest possible cloud is much too small to be freely expanding over an accretion time of $\sim 10^6$ y. It could be gravitationally bound in an excretion disc outside the binary orbit, although it is not known how long such a disc would survive. Alternatively, accretion of helium or carbon-oxygen matter could proceed much faster because of the reduced thermonuclear energy release, efficient neutrino cooling (in burning of carbon and heavier elements) and the difficulty of igniting these fuels. Accretion of heavier elements resembles degenerate dwarf coalescence more than conventional mass transfer, and might be

rapid enough (gravitational radiation-driven coalescence lasts ~ 30 y) that escaping matter would still be sufficiently close and dense when the final collapse occurred, even were it freely escaping.

Apart from their gamma-ray emission, such events might roughly resemble supernovae, as energy deposited in the cloud is thermalized and radiated. If classed as supernovae, they may be of unusual type and subtypical luminosity and duration (because the cloud is probably less massive than typical supernova envelopes). The predicted gravitational wave emission of a long GRB, produced by AIC, is $\sim 10^{-9} M_\odot c^2$ (Katz 1980, Burrows & Hayes 1996), or even less if no matter is expelled.

5. Short GRB

Short GRB require a new mechanism. The requirement of producing $\sim 10^{51}$ erg of soft gamma-rays, and $\sim 10^{53}$ erg of neutrinos if the NFDS process is assumed, points to a catastrophic event involving one or more neutron stars; half the energy must be released in 10 ms in at least a few GRB. We suggest the collision of two neutron stars, probably occurring in a very dense cluster of stars.

5.1. Colliding neutron stars

Unlike a mass transfer binary, colliding neutron stars will not generally be surrounded by a massive cloud. Any such cloud would probably be dispersed when the neutron stars were born; if not, it would rapidly be disrupted in a dense star cluster. Hence collisional production of pions and high energy gamma-rays is not expected from short GRB, consistent with the rarity of their detection by COMPTEL (the few detections of short GRB might be of the high energy tail of the soft gamma-ray emission at ~ 1 MeV) and the absence of

their detection by EGRET or OSSE.

Colliding neutron stars move on nearly parabolic orbits before collision. For masses of $1.4M_\odot$ and typical equations of state (Wiringa, Fiks & Fabrocini 1988) they have velocities (with respect to their center of mass) of $\approx 0.62c$ at contact, normally directed in a head-on collision. This is mildly supersonic in matter with the typical mean neutron star density $\rho_{ns} \approx 7 \times 10^{14}$ g cm^{-3}, for which these equations of state yield a sound speed $\approx 0.45c$. The resulting shock, requiring a supersonic velocity of convergence not found in coalescing binary neutron stars, is Nature's way of making the large dissipation required for a GRB from a small viscosity.

The collision of two neutron stars is a very complex process, involving a strongly non-ideal equation of state, three-dimensional (unless the collision is head-on) hydrodynamics, and significant effects of general relativity. However, a rough estimate may be useful. The potential energy density attributable to the encounter is $GM\rho_{ns}/s$, where M is the mass of each neutron star and s a mean separation. The internal energy of a shock-heated neutron star interior is $\frac{11}{4}aT^4$ if only photon and electron and muon neutrino (and anti-neutrino) specific heats are considered. This yields an under-estimate of the internal energy, for it neglects the contributions of all charged particles, but is unlikely to be far wrong: the high Fermi energies of neutrons and electrons reduce their specific heats significantly from their nondegenerate values and limit the production of electron-positron pairs, protons are scarce, and muon pairs are massive enough that comparatively few are produced.

If, in addition, we neglect the increase in density upon collision and the fraction of the energy release which appears as adiabatic compression of the degenerate matter rather than as thermal energy, we can equate the available and thermal energy densities:

$$\frac{GM\rho_{ns}}{s} = \frac{11}{4}aT^4. \tag{3}$$

For $M = 1.4M_\odot$, $\rho_{ns} = 7 \times 10^{14}$ g cm^{-3} and $s = 2 \times 10^6$ cm (corresponding to first contact

in the absence of tidal distortion) we find $k_BT \approx 115$ MeV. Some of our approximations tend to cancel but most are in the direction of over-estimating T. The fourth power of T in Eq. 3 is forgiving, so it is probably fair to assume an initial post-collision temperature $k_BT_0 \approx 100$ MeV.

The post-collision configuration has enough energy to recreate its initial state of two neutron stars with zero velocity at infinity. The collision redistributes energy, so that some matter may escape with speed v at infinity, leaving the remainder bound in a single object (which may promptly collapse to a black hole). We take a mass M_e expelled into a solid angle $\hat{\Omega} \leq 4\pi$ sterad, beginning from a region of size r_0 at temperature T_0.

At first this expelled matter is opaque to neutrinos because of its high density and temperature. We estimate its neutrino diffusion time $t_{diff} \approx 3r^2\rho\sigma/(m_Hc)$, where $\sigma \approx 1.7 \times 10^{-38}(k_BT/100\mathrm{MeV})^2$ cm^2 is a mean neutrino interaction cross-section (Janka & Ruffert 1996) and m_H is the nucleon mass. Adopting $\rho \approx 3M_e/(\hat{\Omega}r^3)$ and using the adiabatic cooling law for a relativistic gas of photons and neutrinos $T \propto \rho^{1/3} \propto r^{-1}$, we equate t_{diff} to the hydrodynamic expansion time r/v to estimate the radius r at which most of the internal energy is radiated as neutrinos. The result is

$$r \approx \left(\frac{9}{\hat{\Omega}}\frac{v}{c}\frac{M_e}{m_H}\, 1.7 \times 10^{-26}\right)^{1/4} \left(\frac{k_BT_0}{100\,\mathrm{MeV}}\right)^{1/2} \left(\frac{r_0}{10^6\,\mathrm{cm}}\right)^{1/2} \ \mathrm{cm}. \tag{4}$$

For $\hat{\Omega} = 3$ sterad, $v = 10^{10}$ cm s^{-1}, $M_e = 0.3M_\odot$, $k_BT_0 = 100$ MeV and $r_0 = 10^6$ cm we find $r \approx 5 \times 10^7$ cm. The characteristic width of the neutrino pulse is $\sim r/(2v) \approx 2.5$ ms. The escaping neutrinos can then make a relativistic pair fireball in near-vacuum outside the expelled matter. The neutrino pulse width is a lower bound on the duration of the ultimate GRB. This result is consistent with all GRB durations and is not far from the shortest time-scales observed in GRB; both these facts support this model of the physical processes in short GRB.

A simple estimate shows that the gravitational radiation emitted in the collision of

two neutron stars is $\sim 10^{-2}GM^2/r \sim 10^{51}$ erg into a broad band around ~ 3 KHz. The wave-train would be very different from that of coalescing neutron stars.

5.2. Clusters of neutron stars

A cluster of radius R, containing N stars each with mass M and radius r_s, has an evaporation time

$$t_{ev} \approx \frac{200N}{\ln N} t_{cr}, \tag{5}$$

where $t_{cr} \equiv (R^3/GMN)^{1/2}$ is the crossing time. The time scale for the cluster to evolve by collisions is

$$t_{coll} \approx \frac{R}{r_s} t_{cr}, \tag{6}$$

where the cross-section, allowing for gravitational focusing and nearly parabolic orbits as the neutron stars approach each other, is

$$\sigma \approx r_s R/N \tag{7}$$

if $R/N \gg r_s$, a condition met in all clusters of interest. The total collision rate is

$$\nu_{coll} \sim \left(\frac{GMr_s^2N^3}{R^5}\right)^{1/2} \sim 10^{19}\,\frac{N^{3/2}}{R^{5/2}}\,\mathrm{s}^{-1}. \tag{8}$$

Allowed parameter regimes are shown in Figure 1, in which the stars have been taken to be neutron stars. Relativistic instability is avoided if $\Omega \equiv GMN/(Rc^2) \lesssim 0.1$. The present upper bound (Meegan *et al.* 1995) on the repetition rate of GRB is $\sim 10^{-8}$ s^{-1}. If N_S short GRB were detected over a period t_{obs} with angular accuracy $\delta\theta \ll (4\pi)^{1/2}/N_S$ (so that accidental coincidences are negligible), repetition rates as small as $\sim (N_S t_{obs})^{-1}$ could be detected. This could be a much more stringent bound than that set by BATSE data, whose large positional uncertainties introduce a substantial background of accidental

coincidences. Note, however, that an unknown fraction of neutron star collisions produce observable GRB, so that ν_{coll} may exceed the observed repetition rate of short GRB.

It is unclear whether the cluster evolution time should be longer or shorter than the age of the Universe. The evolution which produced the cluster must, of course, require no more than $\sim 10^{10}$ y, but may be shorter than the evolution time of the GRB-emitting cluster itself (for example, if the earlier evolution involved collisions of less compact stars with larger cross-sections). A long-lived (less dense) cluster may have produced GRB for most of the age of the Universe, and will do so for a very long time, but a certain fraction of shorter-lived clusters would be active at any given time. A good analogy is to globular clusters, which are observed with core collapse times both longer and shorter than the age of the Universe. As a result, it is impossible to exclude any region of Figure 1 except those with $\nu_{coll} \gg 10^{-8}$ s^{-1} or $0.1 \lesssim \Omega$. Clusters with high collision rates may permit the observation of repeating GRB, but there is no *a priori* reason to expect this.

A hypothetical cluster with $N = 10^8$ and $R = 10^{18}$ cm (virial velocity $\approx 2 \times 10^8$ cm/s) has a collision rate $\sim 10^{-14}$ s^{-1} and a lifetime of $\sim 10^{19}$ s. About 10^9 such clusters would be required to produce the observed 10^{-5} short GRB s^{-1} within $z \sim 1$; we cannot exclude that such clusters are commonly found at the centers of galaxies.

Dense clusters involving frequent collisions were discussed (Gold, Axford & Hayes 1965) as a possible origin of quasars, but this is now considered unlikely because stellar collisions do not obviously account for the nonthermal particle acceleration processes which are the essence of the active galactic nucleus phenomenon. (GRB are evidence, however, for particle acceleration in unexpected circumstances!) Quasar models make extreme demands on cluster parameters, for a quasar luminosity of 10^{46} erg s^{-1} requires a collision rate about 10^7 times that of our hypothetical cluster, if each collision releases 10^{53} erg of observable energy (most of which is actually lost as neutrinos, widening the disparity). Cluster models

intended to explain quasars were therefore very dense, and suffered from short lifetimes or relativistic instability. The cluster parameters required to explain GRB as the consequence of neutron star collisions are much less extreme, making such clusters more plausible.

Our hypothetical cluster would probably be undetectable at "cosmological" distances, except for its rare GRB activity. Its mean collisional luminosity, including neutrinos, is only $\sim 10^{39}$ erg s^{-1}. Because the collision cross-section and rate scale as the $+1$ power of the stellar radius (Eq. 7), and the specific binding energy as the -1 power, the collisional luminosity is roughly independent of stellar radius for a cluster of specified R, N and M. A cluster with similar values of these parameters, but less compact stars, would have a similar collisional luminosity but more frequent collisions and more rapid collisional evolution.

It is now considered likely that many galaxies possess massive black holes at their centers, which plausibly grew from dense clusters of stars. When the density becomes high collisions become frequent, and lower density stars are disrupted, leaving only neutron stars and black holes. Dense clusters of evolved stars are plausible precursors to, or companions of, massive black holes; such a black hole has little effect on the structure of the cluster unless the black hole's mass is dominant, a possibility we ignore (it increases the stellar velocities, and requires another parameter to describe it).

6. Thermonuclear Processing

In any NFDS model of GRB some material is accelerated from a dilute fireball above a neutrinosphere to make the relativistic debris shell. In AIC this material has very high entropy; a 10 s wind carrying $10^{-8}\,M_\odot$ from the surface of a neutron star has a density there of ~ 10 g cm^{-3}, but a temperature ~ 1 MeV (Dar *et al.* 1992). A relativistic debris shell produced by a neutron star collision is formed under roughly similar fireball conditions, but

may have a density $\sim 10^3$ g cm^{-3} because its duration may be $\sim 10^{-3}$ s and its surface area of origin may be $\sim 10^{15}$ cm^2 (§5). Expelled neutron star debris, not accelerated to relativistic velocity, has much lower entropy, for it is shock heated to $k_BT \sim 100$ MeV at $\rho \sim 10^{14}$ g cm^{-3}. Rather few baryons are accelerated in ultrarelativistic fireballs, but a much larger mass (perhaps $\sim 0.1\,M_\odot$) of neutron star matter may be expelled at subrelativistic speed.

The nuclear composition of these several sources of matter is of interest. Temperatures of 1 MeV at densities $\ll 10^{-8}$ g cm^{-3} are sufficient to dissociate all nuclei to their constituent neutrons and protons, as will the much higher temperatures found behind shocks in neutron star interiors. The neutrino flux above a neutrinosphere is insufficient to equilibrate neutron and proton numbers in the time available ($\sim 10^{-4}$ s) in the accelerating flow (Weinberg 1972). In contrast, in a shocked neutron star interior with a black-body neutrino density at $k_BT \sim 100$ MeV neutron-proton equilibrium will be achieved rapidly.

In either case, once the matter cools by adiabatic expansion nucleosynthesis will begin. The problem resembles that of nucleosynthesis in the early Universe, but with higher density and shorter time scales. At $k_BT \lesssim 100$ KeV equilibrium favors the reaction $\mathrm{p} + \mathrm{n} \rightarrow \mathrm{D} + \gamma$, and unless the density is very low ($< (4 \times 10^4 t_{exp})^{-1}$ g cm^{-3}), where t_{exp} is the expansion time, all of the less numerous (of p and n) species will be bound as deuterons. Neutron beta decay is very slow, and the familiar network of reactions among p, n, D, T and ^{3}He, which rapidly convert nearly all the D to ^{4}He, follows. The 3-α reaction is too slow to be significant, so the products are almost entirely ^{4}He and either n or p. In contrast to the case of adiabatic decompression of neutron star matter (Eichler *et al.* 1989), no r-process or other heavy nuclei are produced.

The neutrons decay on a length scale (in the local observer's frame) $\sim \Gamma c t_n$, where the neutron decay time $t_n \approx 1000$ s. For relativistic debris this may be comparable to the scale

of shock interaction with the surrounding medium. Neutrons change this interaction. They run ahead of the shock itself because they are not slowed by electromagnetic fields. Their decay introduces a stream of relativistic protons and electrons into the medium; this mix of counterstreaming charged particles is subject to plasma instabilities, and if equipartition is achieved produces synchrotron radiation analogous to (and comparable to) that calculated in shock models of GRB. The subsequent charged particle shock enters a relativistically pre-heated medium, and is weak.

7. Discussion

Our choice of $T_{90} = 10$ s as the dividing line between long and short GRB was made *a priori*, on the basis of the theoretically predicted duration of the neutrino burst from AIC (empirically supported by observations of neutrinos from SN1987A). Our criterion differs from that (2 s) suggested by Kouveliotou *et al.* 1993. They chose this value because it is the observed minimum of the distribution of T_{90}. There are not many GRB with 2 s $< T_{90} <$ 10 s. We found that these have $\langle V/V_{max} \rangle$ indistinguishable from those of even shorter GRB, and that GRB with 10 s $< T_{90} <$ 20 s are indistinguishable from even longer GRB. This supports our choice of a 10 s criterion. It is important, however, to define the division into long and short classes before analyzing the data (as we did), rather than searching for a criterion which maximizes the effect, which would make the error of using an *a posteriori* test of statistical significance.

The division of GRB into two classes implies that statistical tests (for isotropy, repetitions *etc.*) should be performed on each class separately. It is possible that members of each class may have different properties, even though all may radiate by the NFDS process, and effects which are statistically significant for one class may not be significant for the entire population. For example, we determined the angular autocorrelation function

separately for long and short GRB, in order to search for repetitions in each class of source without the statistical interference of random coincidences with members of the other class, but found no statistically significant effect. We also searched for dipole and quadrupole anisotropy in each class, but again found no significant effect.

Each of the models for GRB discussed here probably implies a surrounding gas density, with which the relativistic shock interacts, much greater than the typical interstellar density ~ 1 cm^{-3} usually assumed. For long GRB, a cloud of mass 0.3 $M_\odot$ and radius 10^{15} cm has a mean density $\sim 10^{11}$ cm^{-3}, although out of the binary orbital plane it is likely to be much more dilute. The gas density within a dense cluster of neutron stars is difficult to estimate, but is increased above ordinary interstellar densities by accretion from the surrounding media and by tidal or collisional disruption of the occasional nondegenerate star which wanders into the cluster. The consequences of higher values of the gas density include shorter GRB pulses and more efficient conversion of the kinetic energy of relativistic debris to radiation.

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Table 1: BATSE hardness and higher energy detections; nominal sensitivity ranges are indicated. Data are from the 3B Catalogue.

	$T_{90} < 10$ s	10 s $< T_{90}$
BATSE Hardness Ratio > 10 (0.05–0.3 MeV)	21	1
COMPTEL Detections (1–30 MeV)	4	20
OSSE Detections (0.06–10 MeV)	0	2
EGRET Detections (20–30,000 MeV)	0	6

Table 2: $\langle V/V_{max} \rangle$ for short and long GRB. Data from 3B Catalogue.

	Whole Catalogue	64ms Data	256ms Data	1024ms Data
$T_{90} < 10$ s	0.385 ± 0.019	0.383 ± 0.021	0.373 ± 0.027	0.391 ± 0.022
$T_{90} > 10$ s	0.282 ± 0.014	0.370 ± 0.018	0.305 ± 0.017	0.276 ± 0.014
Difference	0.103 ± 0.024	0.013 ± 0.028	0.069 ± 0.032	0.114 ± 0.026

REFERENCES

Bahcall, J. N., Dyson, F. J., Katz, J. I. & Paczyński, B., 1974 ApJ 189, L17

Burrows, A. & Hayes, J., 1996 Phys. Rev. Lett. in press

Dar, A., Kozlovsky, B. Z., Nussinov, S. & Ramaty, R., 1992 ApJ 388, 164

Eichler, D., Livio, M., Piran, T. & Schramm, D. N., 1989 Nature 340, 126

Gold, T., Axford, W. I. & Ray, E. C., 1965 in Quasi-Stellar Sources and Gravitational Collapse, eds. I. Robinson, A. Schild & E. L. Schucking (U. Chicago Press, Chicago) p. 93

Hurley, K. *et al.*, 1994 Nature 372, 652

Janka, H.-Th. & Ruffert, M. 1996 A&A in press

Katz, J. I., 1973 Nature Phys. Sci. 246, 87

Katz, J. I., 1980 Nature 283, 551

Katz, J. I. 1987 High Energy Astrophysics (Addison-Wesley, Menlo Park) p. 18

Katz, J. I., 1994a ApJ 422, 248

Katz, J. I., 1994b ApJ 432, L27

Kouveliotou, C. *et al.*, 1993 ApJ 413, L101

Mathews, G. J., Marronetti, P., Wilson, J. R. & Rhie, S., 1996 Proc. Third Huntsville Gamma-Ray Burst Symposium, eds. C. Kouveliotou, M. S. Briggs & G. J. Fishman (AIP, New York) in press

Meegan, C. A. *et al.*, 1995 ApJ 446, L15

Meegan, C. A. *et al.*, 1996 ApJS in press

Mészáros, P. & Rees, M. J., 1993 ApJ 405, 278

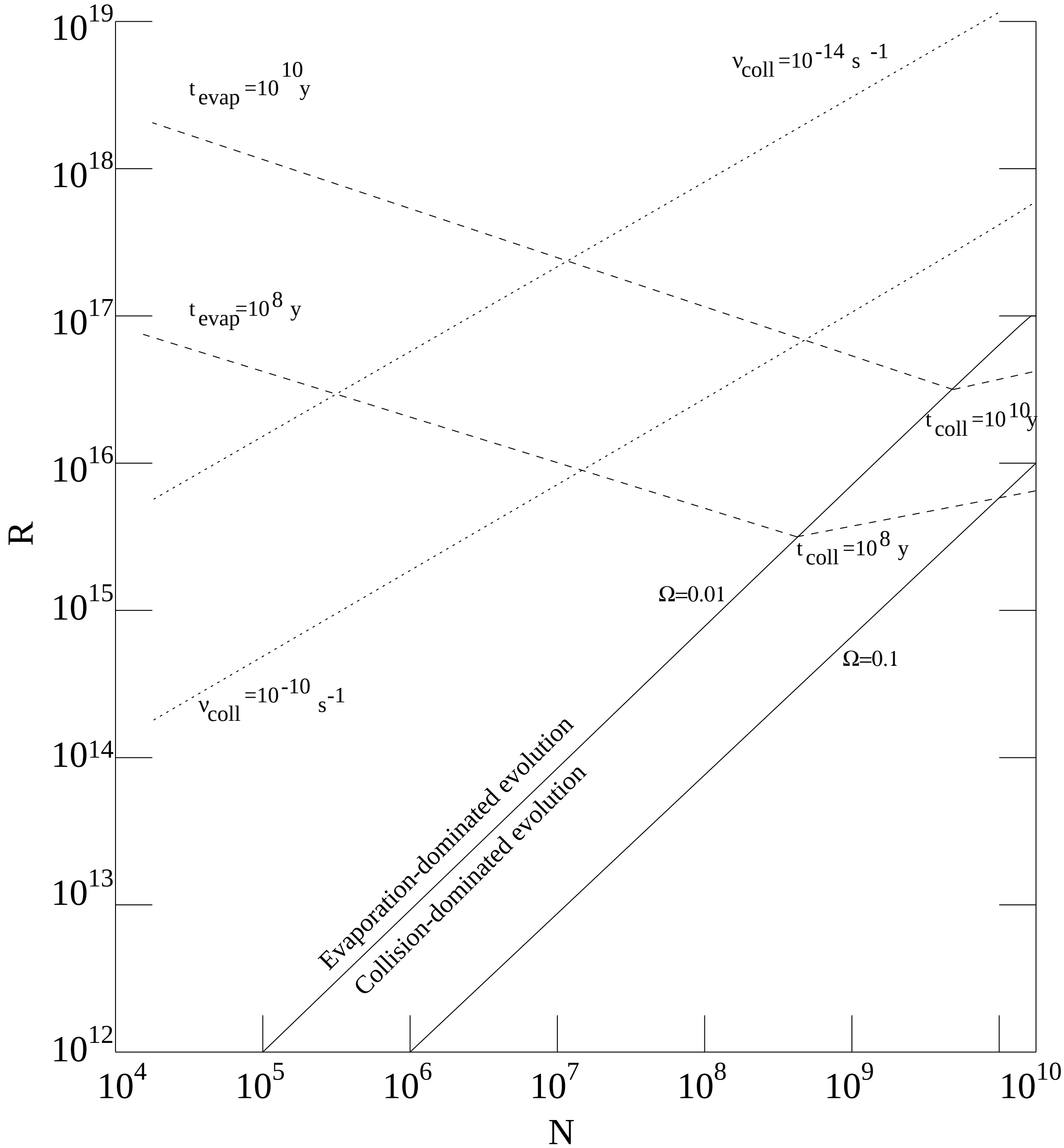
Rees, M. J. & Mészáros, P., 1992 MNRAS 258, 41P

Sari, R. & Piran, T. 1995 ApJ 455, L143

Weinberg, S. 1972 Gravitation and Cosmology (Wiley, New York)

Wiringa, R. B., Fiks, V. & Fabrocini, A. Phys. Rev. C 38, 1010

Fig. 1.— Parameter regimes for clusters of colliding neutron stars.



R
N
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
$t_{evap}=10^{10}$ y
$t_{evap}=10^{8}$ y
$\nu_{coll}=10^{-14}$ s $^{-1}$
$\nu_{coll}=10^{-10}$ s $^{-1}$
$t_{coll}=10^{10}$ y
$t_{coll}=10^{8}$ y
Ω=0.01
Ω=0.1
Evaporation-dominated evolution
Collision-dominated evolution